Applied Thermal Engineering 110 (2017) 921–930

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Numerical investigation into slope-climbing capability of fuel cell hybrid scooter

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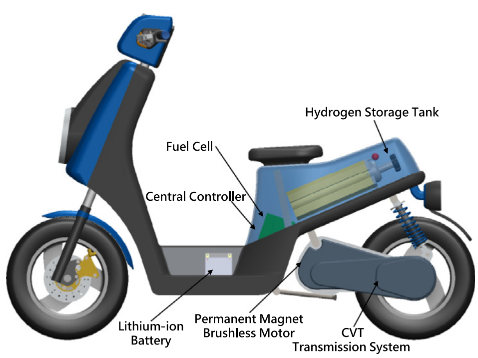
HIGHLIGHTS

- Fuel cell hybrid scooter under typical urban riding conditions simulations.
- Fuel cell hybrid scooter's travel range numerical model design.
- Fuel cell hybrid scooter's motor management and energy management systems design.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 March 2016
Revised 18 August 2016
Accepted 3 September 2016
Available online 4 September 2016

Keywords:
Fuel cell hybrid scooter
Simulation
Hydrogen consumption
Slope inclination angle
Travel range

ABSTRACT

Fuel cell hybrid scooters provide an adequate performance on horizontal road surfaces, but perform less well when climbing slopes. In the present study, the slope-climbing capability of a fuel cell hybrid scooter is examined in simulations. The simulations focus specifically on the effects of the slope inclination angle, riding speed and rider weight on the power consumption, hydrogen consumption, and maximum travel range of the scooter. The validity of the numerical model is confirmed by comparing the numerical results for the power consumption of the scooter with the experimental and analytical results presented in the literature. The simulation results show that the power consumption and hydrogen consumption increase with an increasing slope inclination angle, riding speed and rider weight. Moreover, it is shown that given an initial hydrogen mass of 90 g, a constant riding speed of 40 km h^{-1}, and a rider weight of 60 kg, the maximum travel range reduces from 47 km to 5 km as the slope inclination angle is increased from 0° to 40°. In general, the results presented in this study confirm that the proposed simulation model provides a valid means of characterizing the performance of a fuel cell hybrid scooter under typical urban riding conditions.

1. Introduction

Scooters have many favorable attributes, including a light weight, excellent maneuverability, a small physical size, good fuel efficiency, and a relatively low cost. Thus, as the traffic density in urban environments around the world continues to increase, scooters are seen by many as an ideal solution for their daily transportation needs. However, scooters are a major contributor to air pollution; particularly in developing regions of the world such as India and Asia. With the gradual depletion of the world's supply of natural resources, the need for alternative power sources for

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http://dx.doi.org/10.1016/j.applthermaleng.2016.09.008
1359-4311/

Nomenclature

P_{H_2}	hydrogen partial pressure (atm)	R	armature resistance (Ω)
P_{O_2}	oxygen partial pressure (atm)	$P_{R\text{-}loss}$	copper loss (W)
P_{H_2O}	water vapor partial pressure (atm)	V_L	voltage across the inductor (V)
HP	horsepower (W)	D	duty cycle
T	torque (kg m)	$Fbrk$	braking force (N)
N	rotational speed (rpm)	Fr	external resistance of car) (N)
Z	effective conductors of armature coil in series	$F_{traction}$	driving force (N)
P	pole-pairs	m	mass of car (kg)
Φ_g	effective magnetic flux (wb)	Vx	car speed (m s^{-1})
a	armature coil in parallel	μr	friction coefficient on the ground
I	armature current (A)	Cd	drag coefficient
K_T	torque constant	g	gravity acceleration (9.8 m s^{-2})
E	armature voltage (V)	ρ_{air}	air density (kg m^{-3})
K_E	back emf constant	As	the front area of car) (m^2)
T	load torque (N m)	Vw	wind speed) (m s^{-1})
ω	angular velocity of rotation (rad s^{-1})	P_e	power of fuel cell) (W)
K_M	motor constant	E_{cell}	electromotive potential (V)

automotive and transport applications has emerged as an urgent concern. Fuel-cell-powered scooters (FC scooters) offer the potential for both reducing air pollution and conserving natural resources. As a result, research and development in the FC scooter field has witnessed a rapid growth in recent years [1,2].

Sripakagorn and Limwuthigraijirat [3] conducted an experimental investigation into the performance of two fuel cell hybrid propulsion systems incorporating a battery and a supercapacitor, respectively. The results showed that the two systems yielded a similar fuel consumption and were both capable of delivering the requested load satisfactorily. Shan and Pollet [4] converted a "pure" lead-acid battery electric scooter into a hydrogen fuel cell battery hybrid scooter (HFCHS) in order to investigate the effects of hybridization on the range, performance, running cost, and so on. It was shown that the HFCHS achieved a maximum range of 24 km, a running cost of £0.01 km^{-1} and an energy consumption of 0.11 kW h km^{-1}. Huang et al. [5] constructed a FC scooter with a lithium battery auxiliary power supply and showed that a minimum motor power of 4 kW was necessary to optimize the performance of the FC system components during a simulated 1500 km rough road test. Cheng et al. [6] presented an energy management algorithm for a hybrid FC scooter with a lithium polymer battery. The validity of the proposed approach was demonstrated by implementing the algorithm on the central computer of an actual scooter. Yang et al. [7] presented and validated a control strategy suitable for mass-produced FC hybrid electric scooters. Hwang [8] conducted a detailed numerical investigation into the performance of a vehicle propelled by proton exchange membrane fuel cell (PEMFC) stack and lithium battery pack. The investigations focused on two main issues, namely the design of an appropriate drive train to ensure an adequate performance while minimizing the environmental impact and the effects of different control strategies on the hydrogen consumption and fuel cell system efficiency, respectively. Khateeb et al. [9] developed a macroscopic electrochemical-mechanical model to predict the power demands of an electric scooter by means of MATLAB/Simulink simulations. The validity of the proposed model was confirmed by comparing the simulation results with the results obtained from a conceptual Li-ion battery pack. Fadel and Zhou [10] presented a power management system for FC vehicles based on the fuel mass flow rate. It was shown that by using the fuel mass flow rate rather than the fuel mass consumption as the cost function in the optimization algorithm, the control scheme could function in real-time with no need for the driving cycle to be known in advance. Yu et al. [11] proposed an active power-flow control strategy for three-component (fuel cell, battery and supercapacitor) hybrid vehicles. The simulation results showed that the control strategy achieved a significant energy saving over long driving cycles compared to that of vehicles propelled by just two components (i.e., a fuel cell/-battery or fuel cell/supercapacitor). Lin [12] performed a numerical investigation into the performance of a PEMFC scooter under typical urban driving conditions in Taiwan.

Although many experimental and numerical investigations into various aspects of FC hybrid scooters have been performed, the literature contains relatively little information regarding the performance of FC scooters under typical urban conditions. In practice, however, the performance of FC scooters reduces significantly when slope climbing. Thus, in designing a hybrid FC system for commercialization purposes, the performance of the FC scooter must be assessed under both level and inclined road conditions. Accordingly, the present study constructs a MATLAB/Simulink model of a FC hybrid scooter and then uses the model to investigate the effects of the slope inclination angle (0–40°), riding speed (0–40 km h^{-1}) and rider weight (50–80 kg) on the power consumption, hydrogen consumption and maximum travel range, respectively. In general, the results provide a useful insight into the slope-climbing capability of a typical FC hybrid scooter. Moreover, the results confirm the validity of the proposed numerical model as a tool for assessing the performance of FC hybrid scooters under typical urban riding conditions.

2. Fuel cell scooter and simulation model

2.1. Fuel cell hybrid scooter

Fig. 1 presents a schematic illustration of the FC hybrid scooter considered in the present study. As shown, the major components of interest include a fuel cell stack (48 V, 2.5 kW), a hydrogen storage tank (two bottles; each with an initial hydrogen mass of 45 g), a lithium-ion battery (12 A h), a central controller (8051 chip), a permanent magnet brushless DC motor (maximum torque 10 N m), and a Continuously Variable Transmission (CVT) system.

The motor management and energy management systems of the FC hybrid scooter are shown in Figs. 2 and 3, respectively.